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SOME ASPECTS OF THE STALLING OF MODERN LOW-WING MONOPLANES

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## SOME ASPECTS OF THE STALLING OF MODERN LOW-WING MONOPLANES

By Hartley A. Soulé and Melvin N. Gough

### SUMMARY

The factors affecting the stalling characteristics of modern airplanes are briefly discussed. The effect of present-day design trends is shown and means for improving the stalling characteristics of future airplanes are indicated.

### INTRODUCTION

Stalling has always been one of the most important problems relating to safety, and research on the subject is continually being conducted. The problem has gained particular prominence at the present time because of the reputedly insidious and dangerous stalling characteristics being exhibited by some modern airplanes, particularly those of the low-wing type. It is the purpose of this paper to discuss the known facts concerning stalling and its dependence on the geometric arrangement of the airplanes as an indication of what can be done to ameliorate the present unsatisfactory situation.

All types of airplanes, the older as well as the modern, lose their rolling stability at some angle of attack. When this loss occurs, the airplane rolls into a spiral dive from which recovery can be effected only by reduction of the angle of attack, obtained by nosing down the airplane still farther. Considerable height is lost in the recovery so that the immediate danger depends on the altitude at which the loss occurs. The maneuver is, however, the classical "incipient spin" which, if permitted to persist, becomes a fully developed spin from which there may be no recovery. The presence of this unstable condition near maximum lift constitutes one of the greatest dangers attached to stalling. To the pilot the practical definition of the stall has always been the minimum

speed at which the airplane can be steadily flown in contrast to the technical definition, which defines stall on the basis of the occurrence of the possible minimum speed based on maximum lift regardless of the stability characteristics. The two definitions may differ because rolling instability, although associated with the occurrence of maximum lift, may occur either before, simultaneously with, or after the angle of maximum lift for the complete airplane, or in all three ways at different times on the same airplane, depending on several variables to be discussed.

Basically, the solution of the stalling problem consists of the complete elimination of the rolling instability. This solution does not appear possible with efficient low-drag airfoils. For the time being at least, the presence of the rolling instability must be accepted and the problem must be considered as one of arranging the airplane so that the probability of any pilot's approaching the angle of attack at which the unstable condition occurs is as remote as possible. The present unsatisfactory situation has arisen from the fact that the attempts to clean up airplanes and to increase their efficiency have resulted in the development of a type that not only tends to suppress all phenomena upon which the pilot formerly depended to warn him of the possible loss of the rolling stability but also tends to promote its early occurrence. Thus, inadvertent stalling has become increasingly associated with modern airplanes; and these airplanes, because of their general arrangement and high wing loadings, tend to behave worse when they are stalled.

#### STALL-APPROACH WARNINGS

It is essential that the pilot should in some manner be forewarned of the approach of the stall, particularly in the event that the airplane does exhibit such violent rolling characteristics as have been lately experienced. With older airplanes, say those of 5 or 10 years ago, pilots were warned of the approaching loss of rolling stability, and thus of lateral control, by a combination of the following factors:

1. The speed indication given by the air-speed meter.

2. The nature of the vibration of the airplane and the changes in sound as affected by the propeller, the engine, and the airplane structure.
3. The deterioration of the lateral control and the large variation of elevator force and position as the air speed was reduced and the stall approached.
4. To some extent, the attitude of the airplane, particularly in the full-throttle condition.

Then, as now, the pilot had no direct indication of the angle of attack, which is the real basis for all stalling.

One investigator of this subject, Dr. H. J. van der Maas, has attached relative importance to the nature of warnings by classifying them as "passive" and "active." The air speed is a passive warning; the attitude of the airplane and the deterioration of the aileron and rudder control are passive in that they require the pilot's attention, but they are considerably more active than indications of the air-speed meter. The other warnings, that is, the nature of the vibration and the feel and location of the elevator control, are distinctly active because by their very nature they attract the pilot's attention. Active warnings are, of course, the most desirable. The general characteristics of the modern low-wing airplane are such that they tend to suppress all of these warnings with the exception of the reading of the air-speed meter and the change of attitude. The air-speed indication, aside from being only a passive warning, may also be somewhat misleading should the pilot not appreciate the fact that the stalling speed depends upon the normal acceleration existing. For instance, it is recognized that, inasmuch as the lift must be increased at a given air speed in a turn, the angle of attack is therefore increased over that required for the same air speed in level flight. The maximum lift obtained in a turn must be reached at a higher speed than that necessary for the same lift in level flight. A feasible, but not a particularly satisfactory or practical, means of reducing the possibility of a pilot's being misled by the air speed is to mark the dial with the stalling speeds for various normal accelerations and to use the instrument in conjunction with a sensitive indicating accelerometer;

the air-speed indication, however, would still remain a passive warning. The attitude of the airplane is not particularly useful as a warning except in unaccelerated power-on flight.

## CHARACTERISTICS OF AIRPLANE ARRANGEMENTS

### AFFECTING THE STALL

The manner in which the present trend to aerodynamically clean low-wing monoplanes with highly tapered wings has acted to reduce the stall warnings is best shown by a consideration of the factors upon which the stall warnings depend. These factors are:

1. The wing-stalling characteristics, which influence not only the stall warnings but also the violence of the motion following the stall.
2. The longitudinal-stability characteristics as they affect the elevator force and position.
3. The power loading and the  $L/D$  variation with angle of attack.
4. The regulation of the engine and propeller speed by the use of automatic mixture controls and constant-speed propellers.

### Wing-Stalling Characteristics

The wing-stalling characteristics are important because upon them depends the vibration, or lack of it, in the airplane structure and, to some extent, the variation of elevator force and position at low speed. These factors are, of course, also affected by the position of the tail. It is necessary, and generally the case, that the tail position be designed to fall within the wing wake. Vibration usually occurs when the flow breaks down at the center section of the wing and results from the passage of the turbulent flow produced over the after portion of the wing, the fuselage, and particularly the tail. The problem of obtaining an appreciable vibration of the air-

plane consists in making the center section of the wing stall before the setting in of rolling instability, which accompanies the stall of the complete wing or wing tips. The elevator force and position are affected because a center-section stall is accompanied by a change in the flow over the tail. The downwash is decreased and, depending on tail position, the velocity may be either increased or decreased. The downwash reduction is equivalent to an increase in the longitudinal stability. If the load on the tail is downward, a decrease in the velocity over the tail has the same effect as the reduction of downwash, whereas an increase in the velocity is equivalent to a reduction in the longitudinal stability. Progressive loss of aileron control is also associated with a progressive center-section stall.

The wing-stalling characteristics depend upon a considerable number of factors, not all of which are clearly understood. The more important factors appear to be:

1. The wing plan form.
2. The wing twist.
3. The characteristics of the particular airfoil sections composing the wing.
4. The local interference and the propeller slipstream.

The variables of the plan form are: wing taper, sweepback, and sweepforward. Sweepback appears to have some tendency to promote stalling at the tips prior to stalling at the center section, whereas sweepforward seems to have the reverse effect. These effects, however, appear to be secondary with respect to that of taper. Taper tends to produce higher angles of attack at the tips than at the roots of the wing. Since the local stall depends upon the local angle of attack and not upon the geometric angle of the wing as a whole, the result is that, for a tapered wing with no twist, a premature stall of the tips is promoted. That the effect may be very great is illustrated by the extreme case of a diamond-shape wing, for which theory indicates that the tips will be stalled for all angles of attack except the angle for zero lift. The area at the tips in this particular case is small so that such a wing will not necessarily have rolling instability

at all angles; but rolling instability will occur considerably before the angle of maximum lift.

The obvious method of producing a center-section stall is to arrange the wing so as to assure that the tip sections have an effective angle of attack such as required for them to stall last. One means of obtaining such assurance is to wash out the incidence of the wing tips. This method can be used, however, only where a small decrease in the incidence of the wing tip is required, as in the case of a moderately tapered wing. A large amount of wing twist, such as would be required for a highly tapered wing, is undesirable because it tends to increase the wing drag at high speeds and may destroy the lateral stability of the airplane in that range.

Another means of assuring that the wing tips will stall later than the center section consists in the use of airfoil sections at the wing tip that reach their maximum lift at an appreciably higher angle of attack than those of the wing root. Thus the benefit derived from leading-edge tip slots, which increase the local stalling incidence by the order of  $10^\circ$ , is obvious. The stall-control flap also works on this principle. In this case, however, the angular difference between the stall of the wing tip and of the root is obtained by deforming the root sections so as to decrease the angle of attack at which they reach maximum lift and stall. The stall-control flaps do not seem to offer a particularly good solution because they may not take full advantage of the lifting capabilities of the wing and because of mechanical difficulties, particularly in connection with automatic operation.

The automatic wing-tip slots appear to offer much better possibilities. They have a disadvantage, however, in that it is difficult to obtain good slot opening and closing characteristics without increasing the wing drag. Fixed wing-tip slots are another possibility. These slots eliminate the mechanical features of both the automatic slots and the stall-control flaps but will increase the drag. As they need be installed only in front of the tip section, which is a relatively small part of the entire wing span and area, the drag increase caused by them may be justifiable.

Interferences to the flow tend to produce local

breakdowns. Thus, interference effects at the wing roots will tend to produce a stall at those points and counteract the effects of taper. The modern practice of carefully filleting the wing-fuselage and wing-engine-nacelle junctures and of suppressing all protuberances, such as gas-tank and oil-tank caps and wing-root fittings, has tended to eliminate interference effects. The occurrence of center-section stalls on modern airplanes with high taper ratios simply indicates that, in specific cases, fillets may not completely eliminate the effects of fuselage interference. Fortunate as this condition may be, such specific cases should not be used in making generalizations. The indications are that all airplanes with highly tapered wings tend to stall in the manner indicated by classical wind-tunnel tests of similarly tapered airfoils alone.

Sharp leading edges at the wing roots have been used to interfere with the flow. The use of these sharp leading-edge pieces is advantageous in that they can be applied to existing airplanes and can be adjusted relatively easily to give the desired degree of turbulence and tail vibration.

The propeller slipstream has the effect of reducing the interference. It complicates the problem of producing satisfactory stalling characteristics because the effects are not constant, are large, and are dependent on throttle setting. Wing arrangements that may give satisfactory stall warning, power on, may cause a destructive tail "shake," power off. Conversely and more usually, vibration that produces a warning, power off, may disappear when the throttle is open.

#### LONGITUDINAL-STABILITY CHARACTERISTICS

The static longitudinal-stability characteristics are important because they determine the variation of the stick force and position with speed. With zero stability, the speed of the airplane may change without any change of stick position or control force. Thus, though the pilot holds the stick steady, he has no assurance that the speed may not decrease and that the airplane may not be inadvertently stalled during presumably steady flight. A high degree of stability causes large variations of stick



force and position with speed. These factors cannot be inadvertently overlooked and, when the stick is freed the airplane will return to the original flight speed. The pilot may therefore always check back on his speed simply by permitting the stick some freedom.

In addition to the conditions for straight flight, the possibility of an inadvertent stall in a turn is less for a stable airplane than that for an airplane with zero stability. Inasmuch as the condition for zero stick force is a function of angle of attack of the airplane and not of the airplane speed, the speed for zero stick force, when a stable airplane is put into a turn, will increase with the angle of bank in such a ratio that the airplane will be no nearer the stall in the turn than it was in the original steady-flight condition. Even though the stable airplane were not balanced for zero stick force and even though it were necessary to hold back on the stick, if the same stick force be maintained in the turn, the speed would increase as it would in the case of zero stick force; whereas, if an attempt be made to maintain the same speed, the force would increase - the amount depending on the degree of stability.

Most of the earlier airplanes were biplanes that, happily, had desirable stability characteristics. With these airplanes it was necessary, as the speed was reduced, to exert increasing moments by means of the elevator, which accounted for the increase in stick force and the increase in travel necessary to trim at lower speeds. Development, when it originally led away from biplanes, went to high-wing monoplanes, which have as good inherent stability characteristics as biplanes. The variation of stick force and position characteristic of the high-wing type may be attributed, to a great extent, to the relation between the vertical positions of the center of gravity and of the center of effort, or the aerodynamic center of the wing. It can readily be shown that the stability of a biplane is more or less constant with speed. With the high-wing monoplanes, the stability is inherently greater at high angles of attack and low speeds than at high speeds. This characteristic is particularly desirable in that it gives a large variation of stick force and travel at the lower speeds without making the airplane particularly stiff at high speeds.

Commander W. S. Diehl in a discussion of the problem suggested another characteristic of the earlier airplanes.

that probably helps to account for their favorable stick-force characteristics. He pointed out that, with the slower airplane in the days before flutter became a problem, the elevators were not mass balanced and required a fairly large stick force simply to overcome the weight moment. As the ratio between the aerodynamic and the weight forces on the elevator decreases with speed, it is obvious that the weight results in an apparent increase in the variation of elevator pull required to lower the speed.

It can be theroetically shown that the variation of stability with speed for the low-wing airplane is opposite that for the high-wing airplane. With the low-wing airplane, the stability decreases as the speed is decreased. In general, the designer must lay out the airplane for the more usual cruising condition of flight and, regardless of the wing arrangement, he attempts to obtain the most desirable characteristics in this condition of flight. For a given degree of stability at cruising speed, the low wing therefore has an inherent disadvantage over the other wing arrangements in that very small stick-force variation will be obtained in the vicinity of the stall. Added to these adverse effects of the low-wing position used in modern airplanes is the reduction of the elevator weight moment due to mass balancing of the elevators.

#### Power Loading and Variation of $L/D$

Power loading and the variation of  $L/D$  with angle of attack determine the attitude of the airplane when the stall is approached for both the power-on and the power-off conditions. A low power loading and a high  $L/D$  produce a large angle of climb and consequently a steep nose-up attitude, power on. Because of the abnormal attitude, there is not much danger of unforeseen stalling. Flaps decrease the nose-up attitude by reducing the  $L/D$ . With power off, the attitude of the airplane usually continues to change in a nose-up direction as the speed is reduced almost to the stall even though the flight path is steepening and the angle of attack is increasing. The actual attitudes depend on whether the flaps are up or down. When interference effects cause high drags prior to the stall, the nosing over that occurs just prior to the stall is accentuated, giving the pilot an additional warning.

### Regulation of Engine and Propeller Speed

The regulation of engine speed resulting from the use of constant-speed propellers and automatic mixture controls has eliminated much of the warning the pilot formerly obtained from the variation of engine propeller noise and vibration with speed. Furthermore, the action of the constant-speed propeller itself tends to mask any malfunctioning of the engines that might reduce the power being taken from them. This disadvantage, while applicable for only small decreases in power, reduces the dependency that may be placed on the attitude of the airplane as a stall warning.

When constant-speed propellers are further developed to cover a  $90^{\circ}$  range of angles, it may be possible that another source of danger to modern airplanes will be introduced when the automatic pilot is used in conjunction with the other automatic features. In level flight at cruising speed, the airplane has a definite angle that the automatic pilot tries to maintain. If the engine loses power, the nose tends to drop. The automatic pilot will try to bring the nose up to the original position, thereby increasing the angle of attack and decreasing the speed. With serious loss of power, it is possible for the automatic pilot to stall the airplane.

### Miscellaneous Effects

Some cases have been observed with modern airplanes where the lateral-stability characteristics of the airplane tend to promote a premature stall. The first example of this premature stall is related to the low-wing position and the high wing loadings of modern airplanes, particularly small airplanes of the pursuit category. It has been known for a considerable time that the effective dihedral of a wing depends only partly on the geometric dihedral angle; it is also affected by interference effects set up by the fuselage. In general, the high-wing position tends to give a dihedral effect greater than that indicated by the actual dihedral angle. The low-wing position has the reverse effect and reduces the actual dihedral below that indicated by the wing angle. The magnitude of the effects depends upon the relative sizes of the fuselage and the wing; hence the effect is greatest on the very highly loaded pursuit airplanes.

For an airplane exhibiting negative dihedral effect, any use of the rudder, or for that matter any gust, that starts a skid will cause the advancing wing to drop instead of rise. This drop will result in an effective outward roll, which will increase the angle of attack of the downgoing wing. Then with the normal relations, this outward rolling will generate a yawing moment that will tend to add to the rudder yawing moment. The effects are therefore additive. When skidding occurs at slow speeds, the roll may be continued to the point where the advancing wing tip may stall.

Flaps and landing-gear position also appear to have some influence on the effective dihedral angle, but the extent of the influence is not known at present. In this connection it should be noted that skidding does not usually occur to any extent without the use of the rudder in flight. With one airplane in particular it has been observed that, although the airplane did not have a negative dihedral effect with rudder neutral, the side force on the rudder, coupled with the high rudder position, was sufficient to produce a rolling moment that counteracted the wing rolling moment so that any sideslipping the pilot performed in approaching for a landing usually resulted in a further lowering of the already low wing and the possibility of a premature stall.

In addition, for airplanes equipped with flaps, it has been observed that, as the stall is approached, the rudder effectiveness is apparently lost so that, if a wing drops, it may be impossible to return it to neutral or to prevent turning in the direction of the lowered wing by use of the rudder. When the ailerons are effective, the condition is not particularly dangerous if recognized. The condition is common to most airplanes with flaps and requires further study. A brief consideration of the condition in the light of existing stability theory indicates that it might be a natural consequence of the high lift and the low  $L/D$  of the normal flapped wing. The theory shows that, as the lift coefficient is increased, spiral stability becomes increasingly difficult to obtain and that the motions resulting from spiral instability become increasingly violent. Also, if the spiral is permitted to develop until the wing rolls from the level condition by a certain amount, the inherent yawing moments become greater than the counteracting moments that can be applied with the rudder. If the angle

of bank is exceeded for any reason, say because of a gust or an aileron movement, the same conditions probably apply.

The problem is further complicated by the fact that the flap "shadow," or wake, may blanket the vertical surfaces at low speeds, thus reducing the directional weathercock stability and rudder effectiveness. With small highly loaded airplanes, there may be an additional blanketing of one-half the stabilizer when sideslip sets in. This effect is probably more pronounced when flaps producing high lift, and consequently large downwash, are in operation. When the speed of these airplanes is decreased to the minimum, one wing will drop violently. Simultaneously with the wing drop, the change of air flow over the tail relieves the load on the tail sufficiently to permit the airplane to nose over and automatically unstall.

#### CONCLUDING REMARKS

Basically the stalling problem consists of the elimination of the rolling instability. Actually the rolling instability is not only useless but dangerous and should be avoided, preferably inherently by the design. From this point of view, the nature of the motion following the stall becomes unimportant. The complete elimination of rolling instability, however, does not seem possible. It may be possible, nevertheless, to delay rolling instability to angles of attack that cannot be attained with conventional elevator controls. Another possibility is to limit the elevator control so that rolling instability cannot be reached, regardless of the angle at which it occurs. A satisfactory condition might be effected by either of these suggested methods or by their combination. Another possibility is to return to the pilot the warnings to which he is accustomed, or to develop new ones to replace them. Stall-approach warnings may include auxiliary mechanisms that affect the pilot's senses in the same manner as did the older ones; but the most desirable warnings are those that act directly, eliminating the necessity for mechanisms and the possibility of mechanical failure.

The present emphasis on stalling characteristics is primarily a result of the high taper ratios and the low-wing positions employed on modern airplanes. Compromises regarding these factors should be considered for each par-

ticular design. High taper ratios are advantageous because they lead to inherently rigid wing structures. The advantages, however, are reduced, if not lost, when the taper necessitates the added weight and complication of tip slots or stall-control flaps.

Similarly, it may be desirable to compromise as to wing position. With small low-wing single-engine airplanes, the undoubted benefits obtained by the simplicity of retracting the landing wheels makes it probable that this low-wing arrangement will be adhered to. With large transport airplanes, the wing height relative to the ground has become so large owing to the increases in propeller diameter that there is no need to keep the fuselage above the wing. Lowering the fuselage relative to the wing would, in addition to improving the elevator-force variation, have no effect on the retracting mechanism for the main wheels and, in the case of the level three-wheel landing gear, would simplify the installation of the front wheel.

Much work remains to be done on the stalling problem. Other possibilities worthy of investigation may be uncovered. All the possibilities heretofore mentioned deserve much more detailed study to obtain a more complete understanding of the mechanism of stall. The subject of limiting the elevator control to permit only angles of attack below maximum lift is still one for debate. Even if limited elevator controls were generally conceded to be acceptable, more knowledge would be required to obtain longitudinal stability such that for all flap and power conditions a single elevator limit would be satisfactory. If sufficient elevator control to exceed the angle of maximum lift is desirable and demanded, then a more thorough inspection of the factors affecting elevator control at high angles of attack is necessary.

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